CASE 3: SEPARATION CONTROL OVER A WALL-MOUNTED HUMP

D. Greenblatt, K. B. Paschal, N. W. Schaeffler, A. E. Washburn, J. Harris and C. S. Yao
Flow Physics & Control Branch, NASA Langley Research Center, Hampton, VA 23681-2199

Introduction

Separation control by means of steady suction [1] or zero efflux oscillatory jets [2] is known to be effective in a wide variety of flows under different flow conditions. Control is effective when applied in a nominally two-dimensional manner, for example, at the leading-edge of a wing or at the shoulder of a deflected flap. Despite intuitive understanding of the flow, at present there is no accepted theoretical model that can adequately explain or describe the observed effects of the leading parameters such as reduced suction-rate, or frequency and momentum input. This difficulty stems partly from the turbulent nature of the flows combined with superimposed coherent structures, which are usually driven by at least one instability mechanism. The ever increasing technological importance of these flows has spurned an urgent need to develop turbulence models with a predictive capability. Present attempts to develop such models are hampered in one way or another by incomplete data sets, uncertain or undocumented inflow and boundary conditions, or inadequate flow-field measurements.

This paper attempts to address these issues by conducting an experimental investigation of a low-speed separated flow over a wall-mounted hump model. The model geometry was designed by Seifert & Pack, who measured static and dynamic pressures on the model for a wide range of Reynolds and Mach numbers and control conditions.[3,4] This paper describes the present experimental setup, as well as the types and range of data acquired. Sample data is presented and future work is discussed.

Experimental Setup

The experiment consists of wall-mounted Glauert-Goldschmied type body,[3] mounted between two glass endplates where both leading and trailing edges are faired smoothly with a wind tunnel splitter-plate (see fig. 1). This is a nominally two-dimensional experiment, although there are side-wall effects (3-D flow) near the end-plates. The tunnel dimensions at the test section are 771mm wide by 508mm high, but the hump model is mounted on a splitter-plate (12.7mm thick), yielding a nominal test section height of 382mm (distance from the splitter-plate to the top wall). The splitter-plate extends 1935mm upstream of the model's leading-edge. The trailing edge of the splitter-plate, which is 1129mm downstream of the model's leading-edge, is equipped with a flap (95mm long), which is deflected 24° upwards to reduce circulation around the splitter-plate and avoid separation at the leading-edge. The boundary layer is tripped at splitter-plate leading-edge, resulting in a fully-developed turbulent boundary layer (δ~30.5mm) at 2.14 chord lengths upstream of the model leading-edge. The tunnel medium is air at sea level.

The characteristic reference "chord" length of the model is defined here as the length of the hump on the wall, i.e. c=420mm. Seifert & Pack [3] used the body virtual leading-edge to define their chord length; presently the entire hump length is used as the chord length. As a result of this, the current scaled (non-dimensional) coordinates of the overall body shape are slightly different from those of [3]. A simple rescaling operation can recover it.

The model is 584mm wide with endplates at both sides (each approximately 235mm high and 864mm long). The model is 53.7mm high at its maximum thickness point. Both uncontrolled (baseline) and controlled flow scenarios have been considered under various different conditions for $Re \leq 1{,}114{,}800$ and $M \leq 0.12$. However, detailed flow field measurements were made at Re=929,000, M=0.100. The boundary layer is subjected to a favorable pressure gradient over the front convex portion of the model (fore-body) and separates over a relatively short concave ramp

in the aft part of the body. A slot at approximately the 65% chord station on the model, immediately upstream of the ramp, extends across the entire span (*s*) of the hump. The model was equipped with 165 streamwise and spanwise static pressure ports and 20 dynamic pressure ports in the vicinity of the separated flow region. All pressure transducers were calibrated in-situ prior to each run.

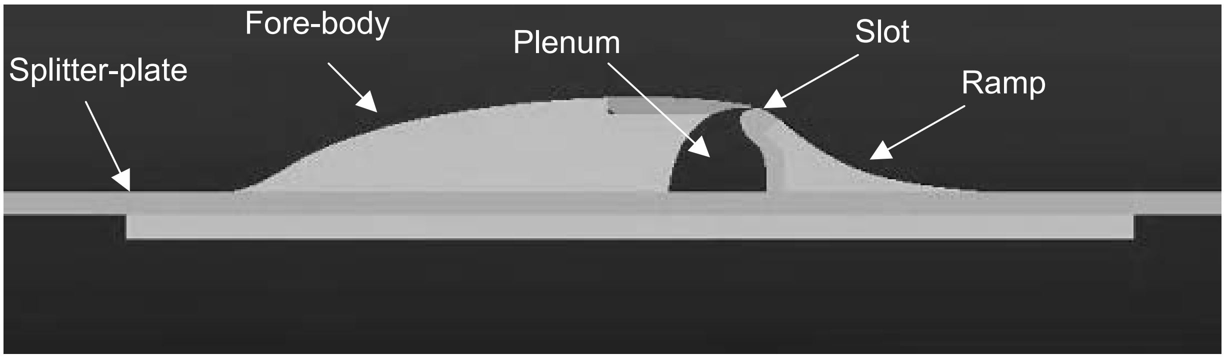


Figure 1: Side view of the model and splitter-plate (endplates not shown)

Separation control is achieved using two methods, namely steady suction and zero efflux oscillatory blowing. Both suction and oscillatory blowing are introduced from the spanwise slot. Steady suction is achieved by means of a suction pump attached to the plenum with the mass flow rate monitored, while zero mass-flux oscillatory suction/blowing is achieved by means of a zero efflux actuator specifically designed to minimize three-dimensional effects near the slot.

Sample Experimental Data

The primary data acquired for this test case were surface static and dynamic pressures, and two-dimensional and stereo (three-dimensional) PIV in the separated and reattachment regions. Limited hot-wire and Pitot-tube data was acquired as an independent check of the PIV flow field results. An oil-film technique was used to determine the reattachment location. In addition, the inflow boundary layer and upper wall (ceiling) boundary layers were documented.

<u>Baseline Results</u>

Fig. 2 shows the baseline (no control) surface pressure data, from both dynamic and static pressure ports, in the separated flow region. The figure shows that there is no significant Reynolds number effect for $Re \geq 557{,}400$ on this model. Also the extent of the separated region is similar to that of ref. [3] at much higher *Re* and a different setup and facility (The reference pressure in [3] was adjusted by 0.266% in order to match their inflow C_P with the present data). The suction peak upstream of the slot, just downstream of $x/c=0.5$, is somewhat higher than that in ref. [3]. The most probable explanation for this is the difference in the ratio of model height to tunnel height for the two cases, namely $h/H=8\%$ [3] versus 13% (present setup). Fluctuation pressures showed similar trends for all cases. The flow was shown to be essentially two-dimensional in that spanwise pressures did not differ materially in the separated region and planes of stereo PIV flow fields in the separated and reattachment regions showed negligible spanwise variation (see e.g. fig. 3a and 3b). Oil-film surface shear measurements in the reattachment region showed an effectively two-dimensional reattachment line at $x/c \approx 1.11$ (shown on fig. 2). The static and dynamic pressures are virtually insensitive to the presence of the slot. This was ascertained by comparing data acquired for the open slot (sealed internally at the bottom of the plenum) and the slot sealed externally (not shown).

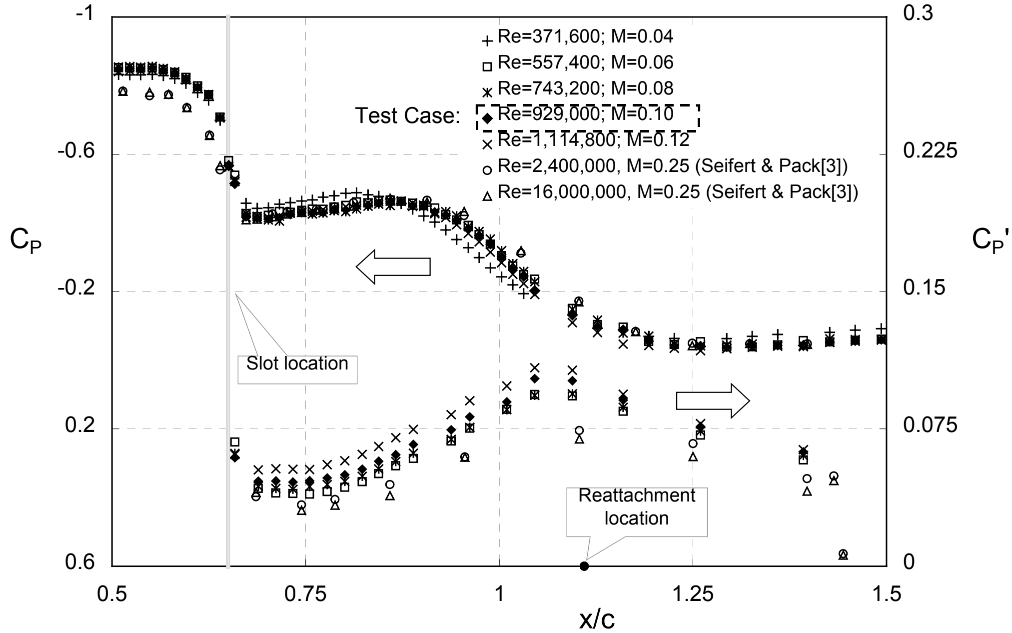


Figure 2. Time-mean and rms surface pressures for the baseline case at various Reynolds numbers.

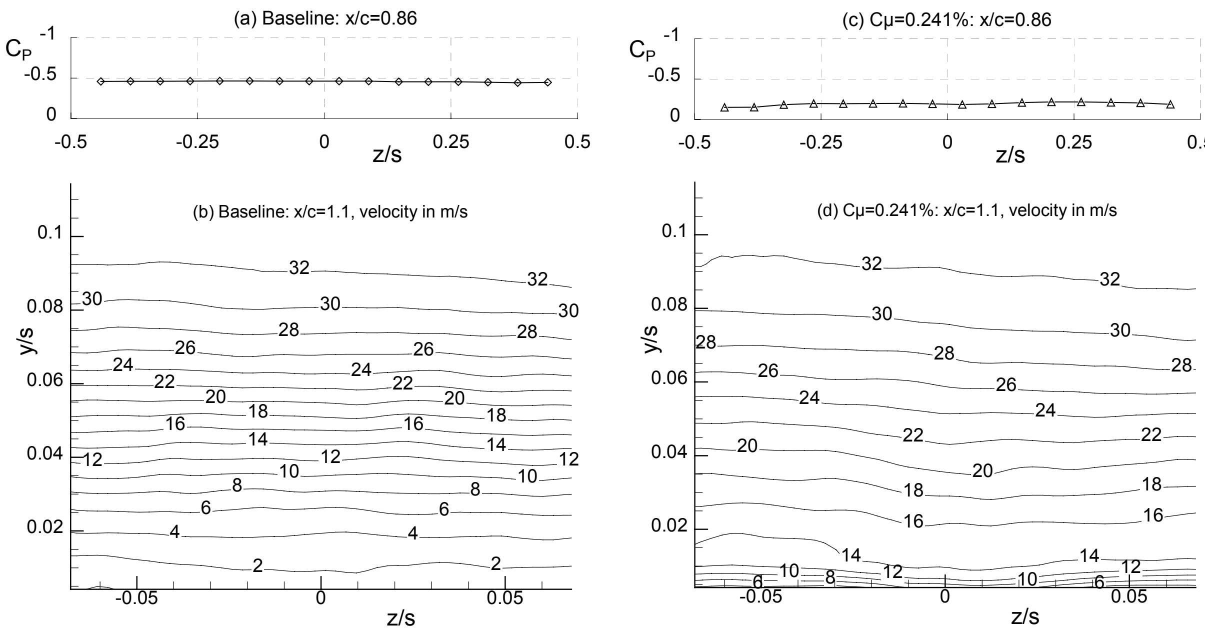


Figure 3. Spanwise ramp pressures and streamwise velocity from stereo PIV in the vicinity of reattachment for the baseline (a,b) and control (c,d) cases.

Control via Steady Suction

For the suction test case, control was applied via the two dimensional slot using a suction rate of 0.01518 kg/s at *Re*=929,000. Furthermore, control was applied for the same dimensionless conditions at different Reynolds numbers (fig. 4). (Suction rates are often expressed as a mass flux coefficient, presently C_m=0.15%. Seifert & Pack [3] used C_μ, to allow direct comparison with oscillatory cases.) There is a small Reynolds number effect that can be discerned in fig. 3, but the trend is towards the higher Reynolds number data.[3] Additional data acquired at higher suction rates (C_μ~0.456%) showed similar trends to those at lower C_μ~0.241%. Near the centerline the flow retains its two-dimensional nature (figs. 3c and 3d).

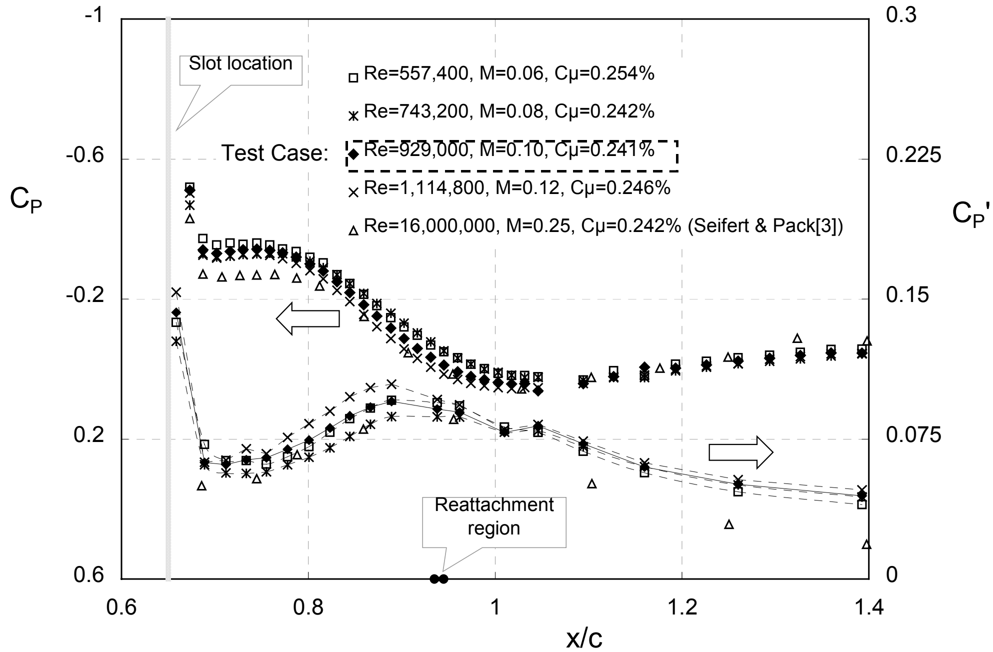
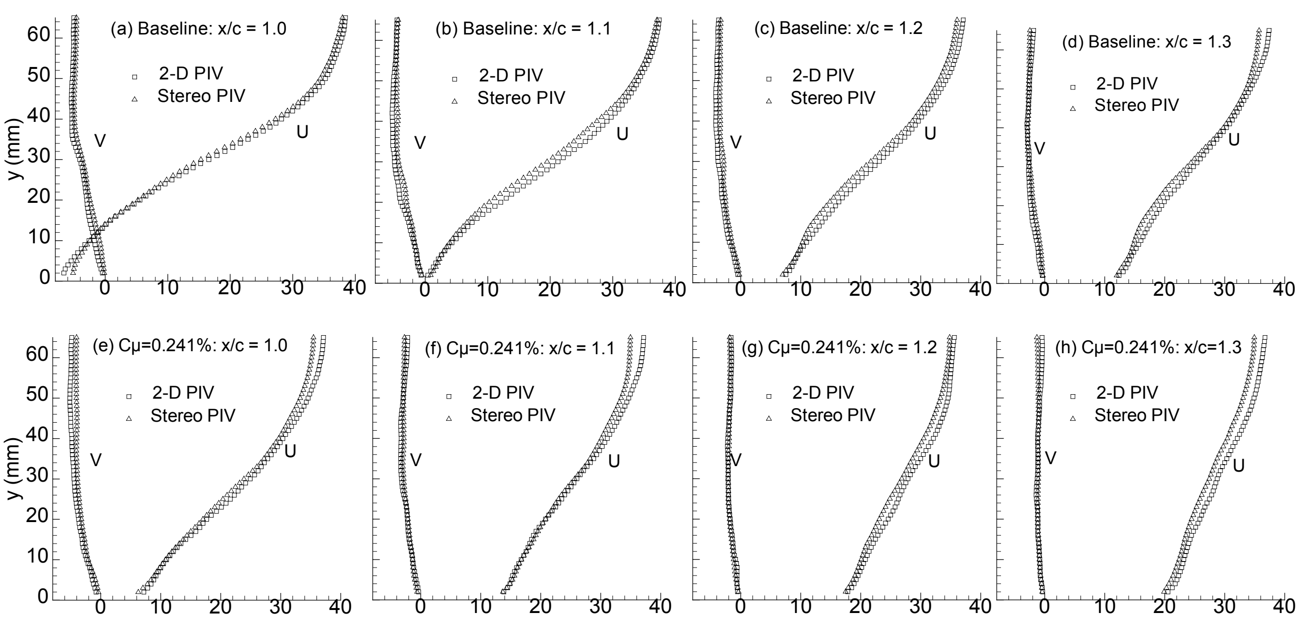


Figure 4. Mean and rms surface pressures for the control case at various Reynolds numbers.

PIV Profiles for Baseline & Control Cases

Examples of two-dimensional (2-D) and stereo (three-dimensional) PIV mean velocity profiles, in the vicinity of reattachment, are shown for baseline and steady suction cases in fig. 5. *U* is the streamwise component and *V* is the component normal to the splitter-plate. Additional 2-D PIV data was acquired from upstream of the slot, continuously throughout the reattachment region. Based on comparisons with Pitot-tube data, errors associated with 2-D profiles were ≤1% of the maximum velocity, while stereo PIV under-predicted mean velocity profiles by as much as 3% of the maximum.



.

Figure 5. 2-D and Stereo PIV mean velocity profiles for the baseline (a-d) and control (e-h) cases in the vicinity of separation and downstream thereof.

Examples of turbulent stresses, corresponding to the velocity profiles above, are shown in fig. 6. A preliminary error analysis, based on comparisons with hot-wire anemometry indicates errors ≤20% of the maximum value.

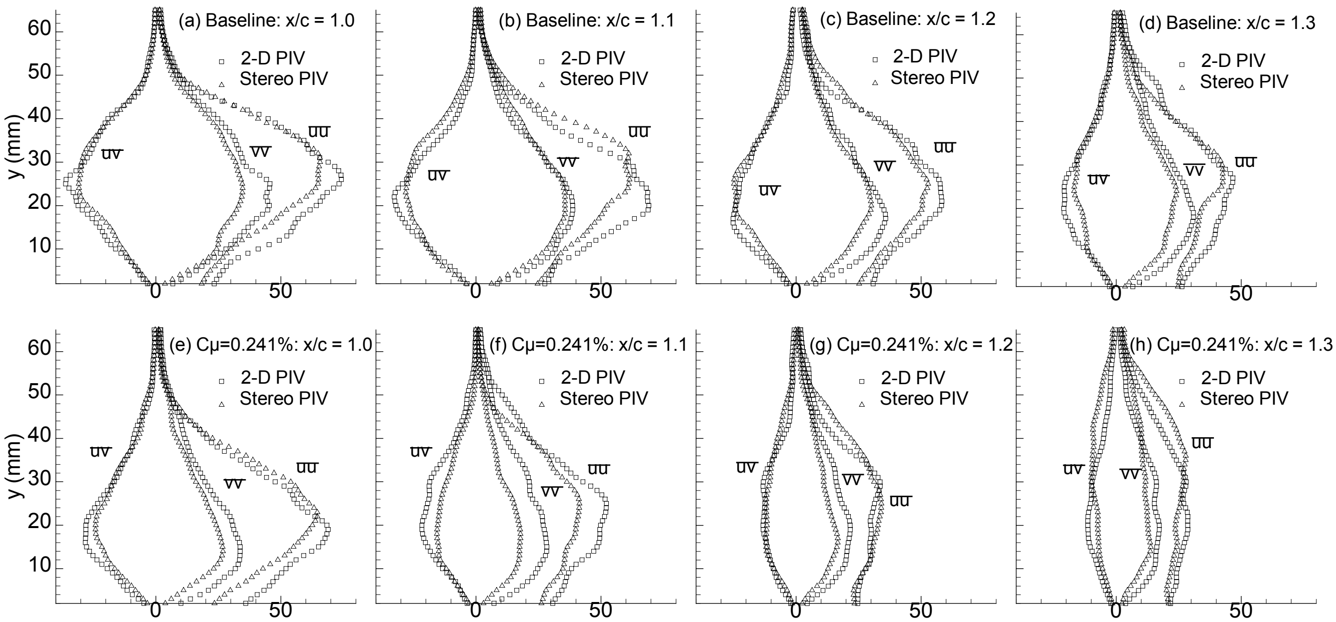


Figure 6. 2-D and Stereo PIV turbulence profiles for the baseline (a-d) and control (e-h) cases in the vicinity of separation and downstream thereof.

Zero-Efflux Oscillatory Forcing

A zero-efflux oscillatory jet is produced by a rigid piston, that is secured to the base of the plenum by means of a flexible membrane. The piston is driven externally by six voice-coil based actuator modules, providing maximum slot velocities of approximately 80m/s at frequencies ranging from 60Hz to 500Hz. At the test condition (nominal peak slot velocity = 26.6m/s; forcing frequency = 138.5Hz), peak slot velocity measurements vary by less than 3% across the span of the slot. Surface pressures and time resolved flow fields are currently being acquired.

References

[1] Lachmann, G. V., "Boundary layer and Flow Control. Its Principles and Application", Volume 1, Pergamon Press, New York, 1961.

[2] Greenblatt, D. and Wygnanski, I., "Control of separation by periodic excitation", *Progress in Aerospace Sciences*, Volume 37, Issue 7, pp. 487-545, 2000.

[3] Seifert, A. and Pack, L. G., "Active Flow Separation Control on Wall-Mounted Hump at High Reynolds Numbers," AIAA Journal, Vol. 40, No. 7, July 2002.

[4] Seifert, A. and Pack, L.G., "Effects of Compressibility and Excitation Slot Location on Active Separation Control at High Reynolds Numbers", Journal of Aircraft Vol. 40, No, 1, pp. 110-119, Jan-Feb 2003.